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New class of low frequency QPOs: signature of nuclear burning or accretion disk instabilities?

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Abstract. We report the discovery of a new class of low frequency quasi-periodic variations of the X-ray flux in the X-ray bursters 4U1608-52 and 4U1636-536. We report also the occasional detection of similar QPO in Aql X-1. The QPOs, associated with the flux variations at the level of percents, are observed at the frequency of $7-9 \cdot 10^{-3}$ Hz. While usually relative amplitude of flux variations is increasing with energy, the newly discovered QPOs are limited to the softest energies (1–5 keV). The observations of 4U1608-52 suggest that these QPOs are present only when the source luminosity/mass accretion rate is within a rather narrow range and they disappear after X-ray bursts. Approximately at the same level of the source luminosity the type I X-ray bursts cease to exist.

Judging from these complex of properties we speculate that a special mode of a nuclear burning at the neutron star surface is behind the observed flux variations. Alternatively some instabilities in the accretion disk may be responsible for these QPOs.

Key words: Accretion, accretion disks – Instabilities – Stars:binaries:general – Stars:classification – Stars:neutron X-rays: general – X-rays: stars

1. Introduction

Since the discovery of the quasi-periodic oscillations (QPO) in the X-ray flux from GX 5-1 (van der Klis et al. 1985, Lewin, van Paradijs & van der Klis 1988) they were considered as an important probe of the inner part of an accretion disk and a region where the accretion disk is interacting with a neutron star surface or magnetosphere (e.g. Alpar&Shaham 1985, for review of the present status of QPO observations and theoretical model see e.g. van der Klis 2000). The characteristic time scales in these regions are short and

the QPOs are usually observed (and expected) at the frequencies of tens of even thousands Hz. The variability at much lower frequency (e.g. $10^{-2}-10^{-3}$ Hz) is also present. In particular in the soft state of accreting neutron star binaries the so called Very Low Frequency Noise (VLFN) is observed at these frequencies (e.g. Hasinger & van der Klis 1989), with an approximately power law dependence of power on frequency and typical RMS variations at the level of percents. Using RXTE data on several accreting neutron star binaries we searched for the low frequency quasi-periodic variations of the X-ray flux and found clear signatures of QPOs with a surprisingly similar frequency in 3 sources. The properties of newly found low frequency QPOs are very distinct from those of “canonical” high frequency QPOs, probably indicating the different underlying physics.

We describe the experimental results in Section 2. In Section 3 we speculate on the possible origin of the low frequency QPOs. Section 4 summarizes our finding.

2. Observations, data analysis and results

In our analysis we used publicly available data of Rossi X-Ray Timing Explorer and EXOSAT observatories. We analyzed ~ 450 ksec of RXTE/PCA observations of 4U1608-52 and ~ 400 ksec of RXTE/PCA observations of 4U1636-536 during the period Mar.1996–Feb.1999. Also we reanalyzed archive EXOSAT/ME observation of Aug.8, 1985.

Two considered X-ray sources 4U1608-52 and 4U1636-536 both are neutron star binaries demonstrating type I X-ray bursts. Below we assume a distance of 4 kpc for 4U1608-52 (e.g. Gottwald et al. 1987) and 5 kpc for 4U1636-536 (e.g. Lawrence et al. 1983, Inoue et al 1984). 4U1636-536 is a relatively stable source with an average flux of approximately ~ 200 mCrab and the luminosity $\sim 10^{37}$ ergs/s (see Fig.1). On the contrary 4U1608-52 is essentially a transient source, changing from quiescent state ($L_x < 10^{33}$ ergs/s, Asai et al. 1996) to the

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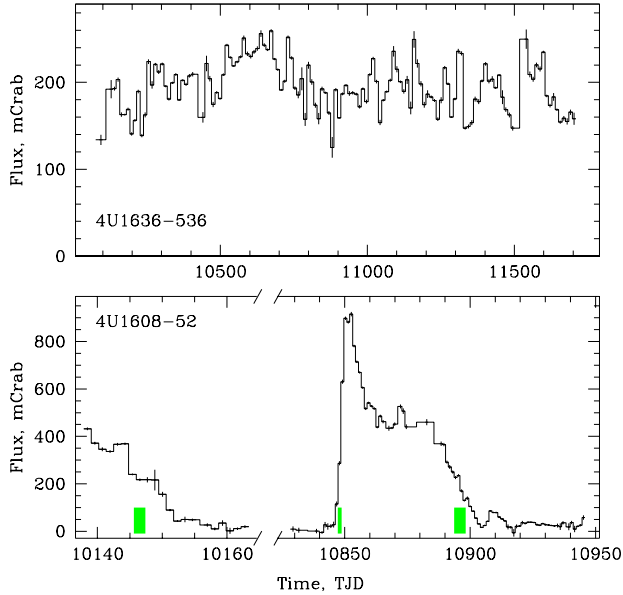


Fig. 1. Light curves of 4U1608-52 and 4U1636-536 according to ASM/RXTE data. The gray boxes on the lower panel (for 4U1608-52) mark the dates of mHz QPO detections.

high state with the X-ray flux more than 10^{37} ergs/s (e.g. Gottwald et al. 1987). The long term light curves of two sources (RXTE/ASM data) are shown in Fig. 1.

The RXTE data analysis was performed with the help of the standard FTOOLS 5.0 package. For the construction of the power density spectra, the sources light curves were cleared out of type I X-ray bursts.

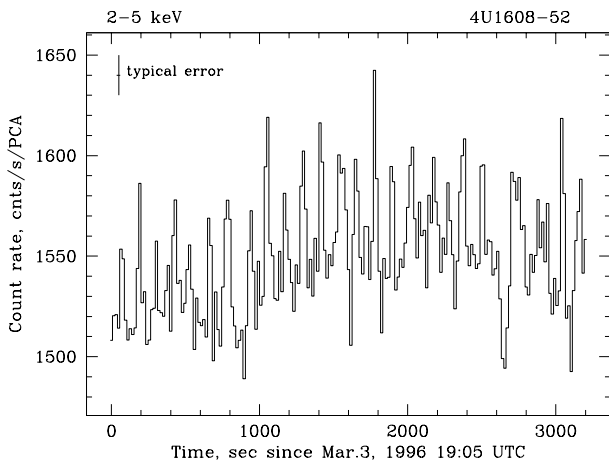


Fig. 2. Segment of light curve of 4U1608-52 with QPO. The quasi-periodical oscillations are clearly seen.

If Fig. 2 we present a small segment of the analyzed light curve of 4U1608-52 in the low energy spectral band of RXTE/PCA ($\sim 2-5$ keV) that clearly demonstrates quasi-periodical oscillations. We clearly detected similar oscillations of X-ray flux from 4U1608-52 during two periods: during the decay phase of X-ray flares of the source in March 1996 and March 1998. Indications for a quasi-periodic variations of the X-ray flux were also found during the rise phase of 1998 X-ray flare (in Feb. 3, 1998 and from Mar. 14, 1998 till Mar. 30, 1998). But a strong, prominent QPO peak on the power spectra was visible only in Mar. 3–6, 1996 and Mar. 24–Mar. 27, 1998 observations. Therefore in the subsequent analysis we use only these data. The dates of QPO detection¹ are shown by gray boxes in the Fig. 1. Neither before nor after these episodes the QPO with similar frequency and width was detected with the approximate 2σ upper limit of $\sim 0.4-0.5$ % in $\sim 2-5$ keV energy band. We note here that the absence of QPOs at lower source flux levels are not due to statistical limitations. Similar QPOs with an RMS of $\sim 1\%$ would be detectable down to the quite low fluxes (down to $\sim 100-200$ cnts/s or $\sim 10-20$ mCrab, i.e. to luminosity $\sim 10^{36}$ ergs/s).

On the contrary, quasi-periodic variations are almost always present in the light curve of 4U1636-536. Unfortunately, the QPO in this source is weaker and it is not always possible to detect the QPO during the single observation with sufficient significance. In Fig. 3 we plot the power spectra of 4U1636-536 in several observational sets. It is seen from the figure that the weak QPO peak is almost always present in the power spectra. Moreover, the centroid frequency of the QPO is very stable $\sim 7-9$ mHz. In the subsequent analysis we used power spectrum of 4U1636-536 averaged over all observations Mar. 96–Feb. 99.

We then analyzed archive data of EXOSAT/ME observation of 4U1636-536 on Aug. 8, 1985. The weak QPO at the frequency of ~ 9 mHz was also found (see Table 1 and Fig. 4). A similar search for the low frequency QPO in the archival EXOSAT/ME observations of 4U1608-52 also showed possible 10 mHz QPO candidate (though weak) during observation on July 5, 1984.

The power density spectra (PDS) for the $2-5$ keV light curves of 4U1636-536 and 4U1608-52 were constructed in the $\sim 10^{-3}-0.03$ Hz frequency range. The PDS were fitted with a model consisting of a power law (VLFN) and a Lorentzian (QPO). The parameters of the detected QPOs in the light curves of 4U1608-52 and 4U1636-536 are presented in Table 1. The power spectra of 4U1608-52 and

¹ including the period during the X-ray flare rise phase in Spring 1998, when some indications for QPOs were also found

Table 1. Parameters of mHz QPOs in the power spectra of 4U1608-52 and 4U1636-536

	4U1608-52		4U1636-536	
Observatory/Instrument	RXTE/PCA	RXTE/PCA	RXTE/PCA	EXOSAT/ME
Energy band	$\sim 2\text{--}5$ keV	$\sim 2\text{--}5$ keV	$\sim 2\text{--}5$ keV	$\sim 0.8\text{--}3.6$ keV
Date	Mar.3–6, 1996	Mar.24–27, 1998	Apr.1996–Feb.1999	Aug.8,1985
Luminosity (3–20 keV), 10^{37} erg/s	0.7–1.1	0.5–0.8	0.7–1.0	0.6
Frequency, mHz	7.5 ± 0.2	7.6 ± 0.3	7.8 ± 0.2	8.8 ± 0.1
Width, mHz	2.6 ± 0.7	1.7 ± 0.8	1.9 ± 0.5	2.0 ± 0.4
Rms Ampl., %	1.85 ± 0.2	1.17 ± 0.2	0.69 ± 0.08	0.9 ± 0.1

4U1636-536 along with the best fit models are shown in Fig. 4.

In order to derive the energy dependence of the QPO amplitude the power density spectra were then constructed in each energy channel of PCA. These power density spectra were fitted with the same model, fixing the slope of the VLFN component, the centroid and width of the QPO peak. The resulting dependencies of mHz QPOs amplitudes on the photon energy are presented in Fig.5.

3. Discussion

The properties of the observed mHz QPOs (mQPOs hereafter) can be summarized as follows:

- Fractional RMS amplitude strongly decreases with energy
- Flux variations in mQPOs are at the level of per cents
- mQPOs seem to be present only at a particular level of source luminosity / mass accretion rate: $L_x \sim 0.5\text{--}1.5 \cdot 10^{37}$ ergs/s.
- mHz QPOs ($f \sim 7\text{--}9 \cdot 10^{-3}$ Hz) with similar properties are found in two “atoll” sources
- The mQPOs with the similar centroid frequencies are present in 4U1608-52 and 4U1636-536 data separated by years (or even ~ 14 years for 4U1636-536).

The decline of fractional RMS amplitude of the QPO with energy (Fig.5) seems to be rather unusual property. Typically for accreting NS LMXBs the fractional RMS amplitude of the variability (at least at frequencies \sim Hz or higher) is increasing with energy (see e.g. Lewin et al. 1992, Berger et al. 1996, Zhang et al. 1996 Revnivtsev, Borozdin & Emelyanov 1999, Homan et al. 1999). The same is true for the Very Low Frequency Noise (VLFN) in 4U1608-52 and 4U1636-536 at the frequencies comparable to the mQPO frequency. This unusual dependence of RMS on energy possibly hints on a very different nature of the flux variations in mQPOs. Below we propose several possible explanations of the observed phenomenon.

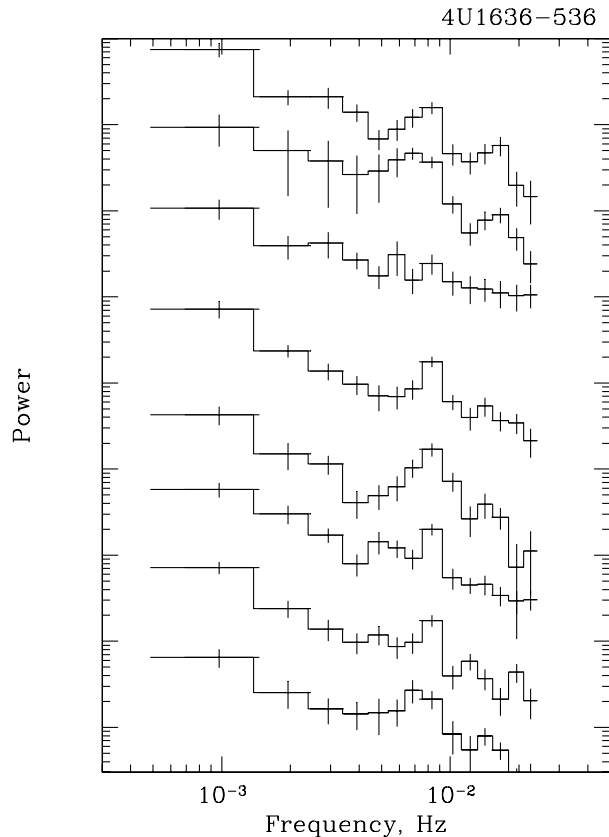


Fig. 3. The power spectra of 4U1636-536 according to data of RXTE/PCA observations from 1996 to 1999. Each power spectrum represents approximately ~ 50 ksec of observations. The power spectra of different observational sets were rescaled for clarity. It is seen that the centroid frequency of the weak QPO peak is considerably stable.

3.1. Quasi-periodic nuclear burning?

The possibility that at high mass accretion rates nuclear burning may cause low frequency luminosity variations has been first suggested by Bildsten 1993,1995 (for overview of the nuclear burning regimes see e.g. Lewin, van

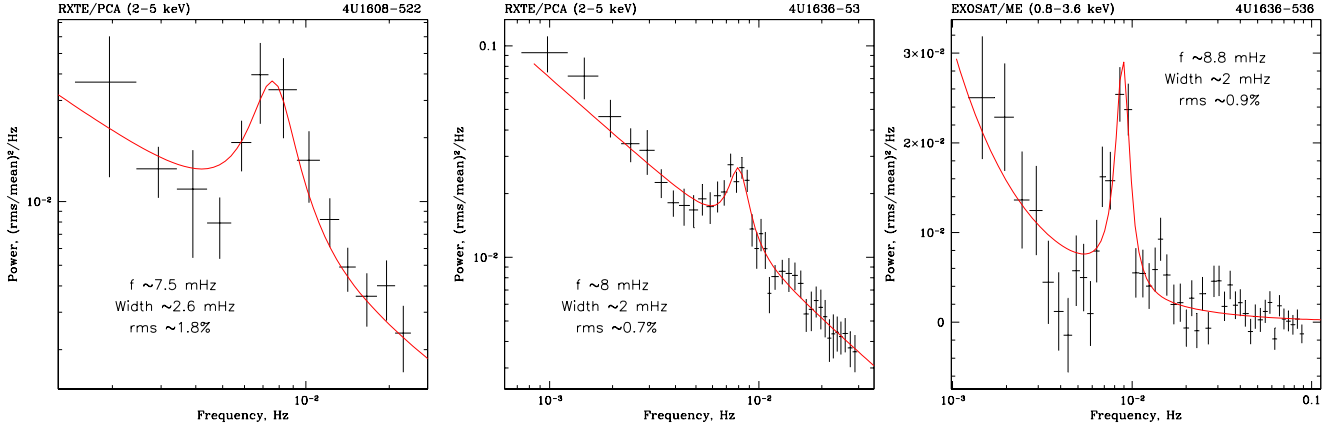


Fig. 4. The power spectra of 4U1608-52 and 4U1636-536 with mHz QPO. *Left panel:* 4U1608-52, observations Mar.3–6, 1996; *middle panel:* 4U1636-536, observations Mar.1996–Feb.1999; *right panel:* 4U1636-536, archive observations of EXOSAT/ME, Aug.8, 1985.

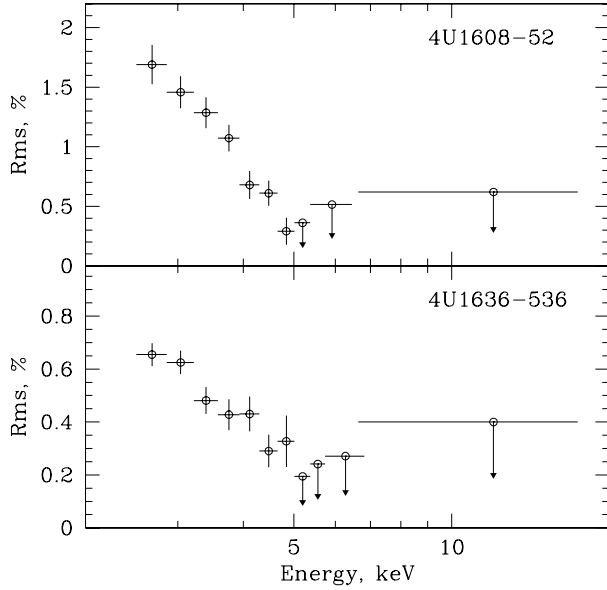


Fig. 5. The dependence of rms amplitude of QPO on the photon energy. For 4U1608-52 the observations March 1996 was used. 2σ upper limits are shown for energies greater than 5 keV.

Paradijs, Taam 1993, Bildsten 1997,2000). Although original suggestion of Bildsten (1993) was that VLFN is the signature of the nuclear burning, we speculate below that newly discovered mHz QPOs correspond to some special mode of nuclear burning which occurs only for a selected range of the mass accretion rate.

First of all modulation of the flux at the level of percents (see Table 1 and Fig.4) is roughly consistent with

expected relative energetics of the accretion and nuclear burning ($L_{\text{acc}}/L_{\text{nuc}}$ of the order of 100). For March 3, 1996 observation of 4U1608-52 the ratio of total source luminosity to the luminosity of the variable component, averaged over the QPO period, was estimated as $L_{\text{tot}}/L_{\text{mQPO}} \sim 145$.

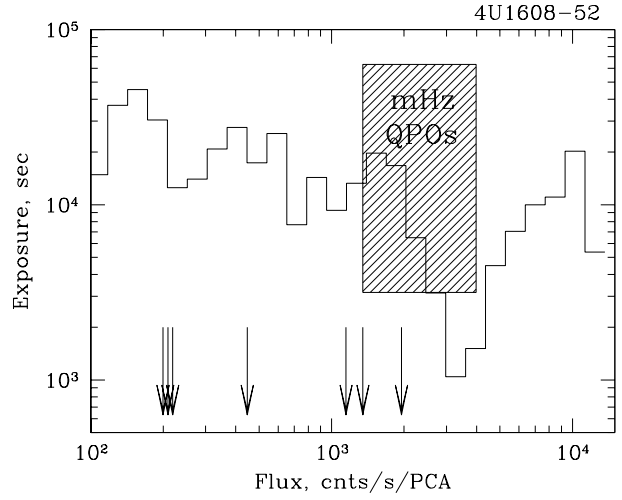


Fig. 6. The PCA/RXTE exposure time for 4U1608-52 at different flux levels. Shaded region shows the range of fluxes when mQPOs were observed. Arrows mark persistent fluxes of the source when Type I bursts were observed.

Secondly it seems that mHz QPOs in 4U1608-52 were present only when the source flux was at a comparable level within a factor of 2-3, while the total range of the source flux variations during RXTE observations spans two orders of magnitude (Fig.1,6). Interestingly enough

that approximately at the same flux level type I X-ray bursts cease to exist as shown in Fig.6. Although the number of bursts detected is not very large the coincidence is striking and may hint on the intimate relation between the changes in the nuclear burning regimes and observed QPOs. This assumption that mHz QPOs are associated with a specific range of mass accretion rates implies that 4U1636-536, which flux does not change much during RXTE observations, by chance has about right accretion rate, favorable for mHz QPOs.

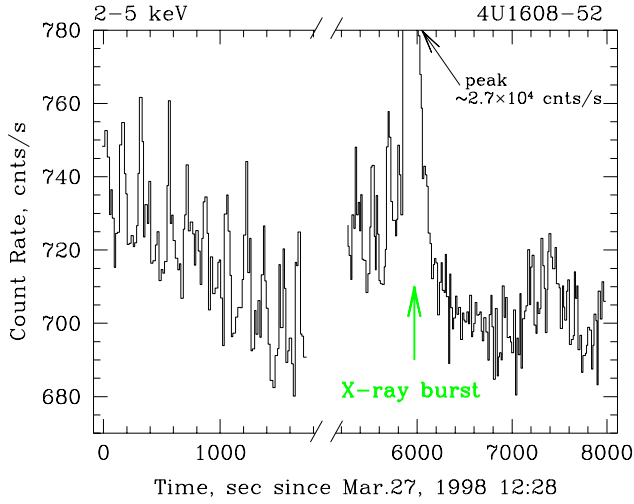


Fig. 7. The light curve of 4U1608-52 before and after X-ray burst of 4U1608-52 on Mar.27, 1998. Note that quasi-periodic variations are clearly visible prior to the burst, but cease after the burst.

Further support of the possible link between nuclear burning and mHz QPOs in 4U1608-52 comes from the analysis of the light curve before and after the type I X-ray burst which occurred during the period when mHz QPOs were detected. The relevant part of the 2–5 keV light curve is shown in Fig.7. During the orbit preceding one when the X-ray burst was detected the quasi-periodic oscillations are clearly visible. Moreover mQPOs are also present immediately before the burst, but cease after the burst. This behavior would naturally fit the assumption that nuclear burning is responsible for mQPOs, if a large fraction of the fuel is consumed during the type I burst and long time is needed to restore the conditions. It is interesting to note that the ratio of peak X-ray fluxes of type I X-ray burst and small “microburst” is of the order of 600–700, and the ratio of released energies is of the order of 150–180.

The change in the X-ray flux variability after a Type I X-ray burst was reported previously by Yu et al. (1999)

for Aquila X-1. Authors reported a drop of the VLFN level after the burst along with the change of the source flux and decrease of the kHz QPO frequency. A possible connection of the low frequency variability with the nuclear burning at the neutron star surface was also mentioned. We reanalyzed archival data of observation of Aql X-1 described in Yu et al. 1999 (Mar.1, 1997) and found a QPO peak at a frequency of ~ 6 –7 mHz. These variations also have a soft spectrum and are undetectable at the energies higher than ~ 7 keV. Moreover significant fraction of the VLFN at these frequencies could be attributed to this QPO. Again, as in the case of 4U1608-52, this QPO-like feature becomes undetectable after the burst. Thus, although satisfactory explanation of all changes occurring during the burst is difficult we concluded the disappearance of the mQPOs is consistent with their “nuclear” nature.

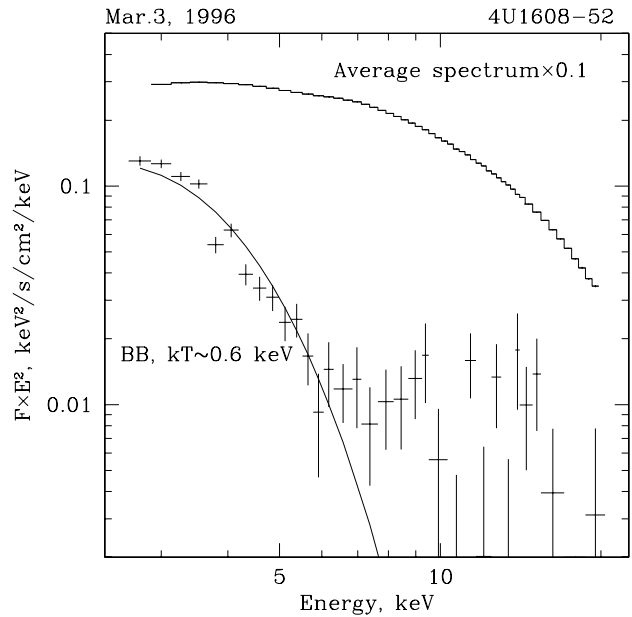


Fig. 8. The energy spectrum of the variable component in 4U1636-536. This spectrum was obtained accumulating spectra during the periods of high and low count rates respectively (see Fig.2) and subtracting one spectrum from another. For comparison the averaged spectrum of the source is shown (scaled down by a factor of 10 for easier comparison with the variable component).

We then examined the spectrum of the “variable” component of the mQPO in 4U1608-52. The spectrum was constructed accumulating spectra during the periods of high and low count rates respectively (see Fig.2) and subtracting one spectrum from another. The resulting spec-

trum is shown in Fig.8.² For comparison in the same plot the averaged spectrum of the source is shown (scaled down by a factor of 10 for easier comparison with the variable component). It is obvious that the “variable” spectrum is much softer than the averaged spectrum. This was of course expected given the strong decline of the RMS with energy (Fig.5). For comparison solid curve shows the black body emission with the temperature of ~ 0.6 keV³. Detailed fit of the soft component is difficult because of the small statistics. It is however certain that the spectrum is softer than the ~ 1.5 –2 keV black body, characteristic for the type I X-ray bursts. The total luminosity of the source during this observation was $\sim 10^{37}$ erg s⁻¹. If few percent modulations are associated with quasi-periodic nuclear burning over the whole neutron star surface than corresponding temperature will be $T \sim (fL/4\pi\sigma r^2)^{1/4} \sim 0.3$ –0.5 keV, where f is the ratio of peak nuclear energy release to the accretion luminosity, $r \sim 8$ –10 km is the neutron star radius, σ is the Stefan–Boltzmann constant. This estimate assumes that no strong sources of heating other than nuclear burning are present. I.e. it assumes that significant part of burning occurs outside the region where accretion energy is released and surface of the neutron star is “preheated” to significantly larger temperature. In the picture of spreading layer on the surface of neutron star (Inogamov & Sunyaev 1999), the kinetic energy of the accreting flow is released in two bright rings equidistant from equator. At luminosities of the order of 10^{37} ergs/s these rings occupy only ~ 15 –20% of the star surface. Nuclear burning could occur in any part of the star surface but in much more deep layers and column densities. Variations of the nuclear burning energy release in the region where main part of the accretion energy is released would result in the variations of the much harder component which dominates the averaged spectrum of the source. This variations could be responsible for anemic harder component barely visible in Fig.8 as an extension of the soft component at energies higher than 6 keV. If this interpretation is correct than weakness of the harder component implies that only small fraction of burning ($\leq 20\%$) occurs in the area where accretion energy is released. We note however that harder component in the variability spectrum should be treated with caution since during selection procedure of high/low count rate periods variations of the harder component (statistical or related to the VLFN) may result

² Note that this spectrum characterizes the amplitude of flux variations as a function of energy and therefore does not necessarily correspond to the really existing spectral component.

³ We note here that very soft component was also found by Yu et al. 1999 by subtracting the spectrum accumulated after the type I burst from the spectrum observed before the burst in Aql X-1

in a slight positive bias and appearance of the weak hard component in the variability spectrum. Unfortunately amplitude of the hard component quasi-period oscillation is in any case very low and statistics is not sufficient to detect a mQPO in hard X-ray flux.

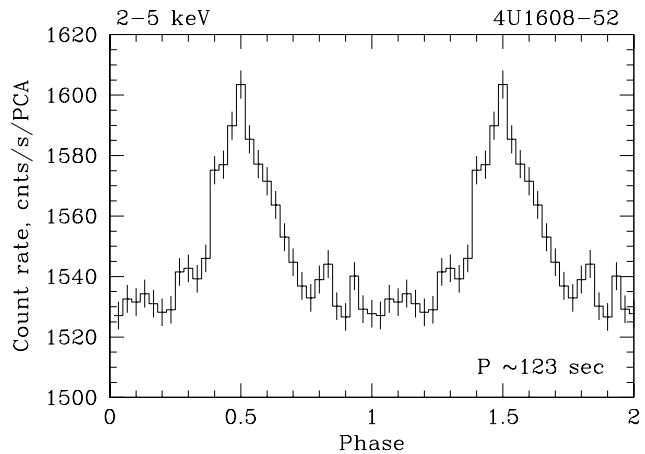


Fig. 9. The profile of the mHz QPO, obtained by folding the light curve of 4U1608-52 obtained during the first orbit of observation on Mar.3, 1996. The errorbars shown are due to pure Poissonian noise.

Finally we examined the characteristic shape of the mQPO in 4U1608-52 using the portion of the light curve where individual QPO profiles are clearly visible. The light curve was divided into pieces with the duration of $(8.13 \cdot 10^{-3} \text{ Hz})^{-1} \sim 123$ s. The phase of the profile in each piece was then calculated, comparing the observed profile with a sine wave, and profiles with a proper shift of phase were coadded. The resulting QPO profile is shown in Fig.9. Experiments with various template profiles used for determining the phases of individual pulses resulted in moderate variations in the averaged pulse profile (as expected given the limited statistics of the data set). The characteristic features of the profile, namely narrower peaks and more extended valleys are however robust against almost any choice of the procedure used to construct the averaged profile. There is also marginal evidence for asymmetry of the peaks: steeper rise and shallower decline. It is interesting that this profile bears some similarity to the time dependent energy release plots of Bildsten 1995 (see his Figure 5a), calculated in approximation of a one-dimensional none-convective model. However, the conditions assumed for these plots, namely the mass accretion rate at the Eddington level and the neutron star boundary preheated to the temperature of more than 10^8 K, are markedly different from what we discuss here.

Thus there are at least several observational facts which seem to be consistent with the association of the mQPOs with the quasi-periodic burning of the nuclear matter at the neutron star surface. It is unclear however what process defines the time scale of ~ 2 minutes, which is surprisingly stable (and even similar for two different sources), why the burning is quasi-periodic and present only in the narrow range of the mass accretion rates.

If the nuclear burning is not uniform over the neutron star surface one may expect asymmetries in the distribution of hot spots and as a result coherent pulsation with the neutron star rotation period, as it is in reality observed during type I X-ray bursts (see e.g. Strohmayer 1999). We tried to search the 4U1636-536 data (type I X-ray bursts excluded) for coherent pulsation, but this search yielded only an upper limit on the modulations in the coherent signal of $\leq 0.2\%$ (2σ ; Lorentzian profile with $f = 580$ Hz, $\Delta f = 1$ Hz) pulse fraction for the 2–5 keV range. This result sets the limit on the uniformity of the energy release on the neutron star surface. However it is not very stringent given the small $\sim 0.7\%$ (see Table 1) contribution of the nuclear burning to the source luminosity.

Trying to understand the nature of unstable nuclear burning we see two simplest possible modes:

- unsuccessful ignitions time to time occur in the different parts of the freshly accreted fuel. Flame fades after burning fuel only on a small surface area. Whole stock of fuel is waiting for successful flame front able to propagate through the whole surface of the star. It is obvious that such a picture could not produce quasiperiodic oscillations. It should be much more stochastic in nature and could produce only broad band noise.
- the unstable helium shell burning occurs at some depth in the freshly accreted fuel. The flame propagates over the whole surface of the star. In this case it is possible to expect quasiperiodicity. However observation of the normal type I X-Ray burst after long series of microbursts (see Fig. 7) restricts strongly possible models of shell burning. Most important consequence is that unstable shell burning occurs below the main fuel stock and does not influence it until conditions for the strong burst materialise. In addition this picture requires that only small part of fuel is processed during the shell burning leaving enough fuel for stronger type I burst. Questions about flame propagation through the thin shell are also not simple.

If the unstable nuclear burning interpretation is correct than one can make two obvious predictions:

- Other NS LMXB may have such QPOs when in the state with a certain flux level. For 4U1608-52 and

4U1636-536 the observed 3–20 keV luminosity was $\sim 0.5\text{--}1.5 \cdot 10^{37}$ ergs/s when mQPOs were observed.

- The low frequency QPOs with similar properties (in particular with a much softer spectrum than the average one) should be absent in black hole candidates.

3.2. Disk instabilities

Although there are several observational indications that mQPOs may be related with nuclear burning on the surface of the neutron star the observations do not provide robust enough proof of this interpretation. We briefly discuss below few other scenarios.

The soft spectrum of the variable component (much softer than the averaged spectrum) may be hinting on the possible contribution of the optically thick accretion disk emission to the variable component. In this case we also can expect that powerful type I X-ray burst could lead to disappearance of disk instabilities for some period.

We note here that variations of the soft component on the time scales of 100–1000 s have been observed e.g. in the galactic black hole candidate GRS 1915+105 (Belloni et al. 1997, Trudolyubov, Churazov & Gilfanov 1999, Munro et al. 1999), which are thought to be associated with the motion of the inner boundary of the optically thick accretion disk. It is not clear however if these variations have the same nature as mQPOs discussed above. In GRS 1915+105 these variations appear when the average source luminosity is close to the Eddington limit, while the QPO discussed above were observed in sources with the luminosity of only $\sim 0.1L_{\text{edd}}$. The amplitude of variations observed in GRS 1915+105 is very large - more than an order of magnitude.

3.3. Other possible scenarios

It is interesting that variations of the photoelectric absorption at the level of $N_{\text{H}}L \sim 3 \cdot 10^{21} \text{ cm}^{-2}$ are capable to reproduce approximately the required dependence of the RMS on energy. It is not clear however what kind of process can cause quasi-periodic variations of the absorption on the time scales of minutes, especially given the stability of the mQPO frequency.

Variations of mass accretion rate in the optically thick accretion disk may also be responsible for the observed variations. However the amplitude of variations of the harder component, presumably coming from the boundary layer, is at least factor of 5 lower than that for the soft component. This makes the variations of mass accretion rate an unlikely reason for the observed mQPOs.

4. Conclusions

New type of very low frequency QPOs has been discovered in at least two “atoll” sources: 4U1608-52 and 4U1636-536 with essentially the same frequency $f \sim 7-9 \cdot 10^{-3}$ Hz. These QPOs have a very soft spectrum, RMS amplitude of variations at the level of per cent and seems to be present only at a certain level of the mass accretion rate. We suggest that these quasi-periodic variations might be related to the special regime of the nuclear burning on the neutron star surface or some instability in the optically thick accretion disk.

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